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HIGH VELOCITY PENETRATION INTO FIBRE-REINFORCED CONCRETE MATERIALS - PROTECTION OF BUILDINGS

William F. Anderson, Alan J. Watson, Paul J. Armstrong

Department of Civil and Structural Engineering
University of Sheffield, U.K.

ABSTRACT

Fibre reinforced concrete suitable for spraying onto existing structures is being examined to assess its resistance to penetration by 7.62mm diameter armour piercing projectiles. A major test programme is being carried out to examine the influence of aggregate type and fibre type. For each aggregate/fibre combination a statistical method is being used to plan test series which will lead to optimization of the concrete in terms of water/cement ratio, fibre content and aggregate/cement ratio. The minimum thickness of optimized concretes to resist penetration by the projectile and minimise spall and scabbing, will be determined. The mechanics of the impact and penetration event are being studied and a possible method of deflecting the projectile within the concrete is suggested.

INTRODUCTION

During the course of its useful life, a structure, particularly a military one, may be subjected to attack from small arms fire, or perhaps indirect impact from close-proximity explosions. Hence, high-risk structures should be constructed from impact resistant materials, and the capability to rapidly upgrade the protection afforded by an existing structure would be advantageous. Any such impact resistant material must be able to contain several different facets of the impact event. It must be able to resist perforation from the projectile, it must be of sufficient thickness to resist tensile scabbing from the back face and it must also be cohesive enough to prevent spalling material flying from the front face, both because this material may be dangerous in itself and also because it leads to a local weakening which may then be breached by repeated impact.

Concrete has a reasonable resistance to projectile penetration, due to its relatively homogeneous and massive properties. So far as the front and rear face damage is concerned, however, the low tensile strength of an ordinary concrete matrix ensures that a large amount of material is ejected from the slab faces with a velocity high enough to be potentially dangerous. Incorporation of fibres into the concrete matrix has been shown to considerably reduce the scabbing and spalling associated with dynamic loading of concrete (1, 2). In general, fibres act to increase the toughness of the composite material by improving the tensile properties of normal concrete, absorbing the stress wave energy by either pulling out of the matrix or perhaps by necking and breaking, depending upon the characteristics of the particular fibre.

Many different types of fibre are available commercially, the properties of the fibre reinforced concrete being dependent not only on the standard concrete variables such as aggregate size and type, aggregate/cement ratio and water/cement ratio, but also on the type, aspect ratio and proportion of the included fibres. A comprehensive testing programme is being carried out to study the effects of these variables and to optimize the fibre reinforced concrete to minimise penetration by 7.62mm NATO armour piercing bullets impacting at approximately 800 m/s. Attempts are being made to examine the mechanics of impact and penetration, so as to understand the failure modes of the fibre reinforced concrete under dynamic loading.

VARIABLES CONSIDERED

In order to fully utilise the adaptability of the optimum material, it was felt that a concrete suitable for sprayed application should be developed, since this would be equally useful for new construction and also for quickly reinforcing existing structures.

Aggregates

To ensure easy application by either the 'wet' or 'dry' spraying process, and to allow a reasonable fibre distribution through the matrix a Concrete Society (3) recommendation of a maximum aggregate size of 10mm has been adopted.

Tests on rock aggregate/elastomer composites subjected to impact by projectiles similar to those used in this study, showed that resistance to penetration was a function of the rock aggregate hardness (4). In order to examine the effect of aggregate hardness on the penetration resistance of fibre reinforced concrete, crushed basalt (relatively hard) and crushed limestone (relatively soft) were chosen as aggregates. The shape of the aggregate particles has an effect on the concrete bond also, and thus on the homogeneity of the

composite. Since the crushed rock aggregates are both angular in shape, a rounded river gravel is included in the study to give a comparison. Aggregate/cement ratios vary from 1:3.0 to 1:5.0 in the statistically based test plans.

Fibres

Since it is impractical to include all the commercially available fibre types in an experimental series, various constraints had to be used to select the materials to be tested. On grounds of health and/or durability, vegetable, asbestos and glass fibre materials were rejected, whilst carbon fibre was rejected because it was considered that the likely high fibre content required for the intended purpose would render the unit cost of the fibrous composite too high to be viable. Finally three types of steel fibre, one type of polypropylene fibre and two lengths of the organic polyamide fibre, KEVLAR 29, were chosen for detailed examination. Where appropriate, a length: diameter ratio of 100 was selected to give a composite which could reasonably be mixed in both a field and laboratory situation.

Cement Matrix

In order to ensure that the optimum fibre reinforced concrete can have universal application, Ordinary Portland Cement is being used and it was initially assumed that the type of fine aggregate used would be unimportant. A range of water/cement ratios between 0.35 to 0.50 by weight is recommended by the Concrete Society (3), for ordinary sprayed concrete. However, due to the apparent decrease in workability caused by the inclusion of large volumes of reinforcing fibre, a range between 0.35 to 0.70 was selected for the main statistical series.

OPTIMIZATION OF THE VARIABLES

For each combination of fibre type (six varieties) and aggregate type (three varieties) it is necessary to optimize the water/cement ratio, aggregate/cement ratio and fibre content. To give a reasonable range of these last three variables it was decided that specimens should be prepared with five levels of each variable. This gives 5^3 (=125) possible combinations for each particular fibre and aggregate. Since it would be unacceptable to test all of these combinations (a total of 2,250 tests) a statistical method known as surface response theory has been used to plan a programme. Details of this method have been given by Cochran and Cox (5). For each of the eighteen fibre/aggregate combinations a rotatable design utilising 14 extreme combinations and 6 mean combinations of the mix design parameters is used to indicate the combination of mix design parameters which will be most effective in reducing projectile penetration. The response surface derived from the actual test results may not indicate an optimum mix within its (star-shaped) boundaries. Thus the optimum mix design may be indicated as not part of the actually tested range. In this case a "corner filling" technique as described by Anderson et al (4) may be used to identify and check the optimum mix.

SPECIMEN PREPARATION

In a full scale structure, the fibre-reinforced concrete would be applied over a large area, hence it was conisdered vital that local and global effects were separated in the laboratory tests, only local effects being considered important. For this reason slabs of various plan dimensions were tested, using a typical steel fibre reinforced concrete mix to determine the minimum target area required to ensure that gross cracking did not occur in most cases. In conjunction with these tests, slabs of various thicknesses were tested in order to obtain a value at which perforation was unlikely to occur in most cases. As a result of these tests, a standard specimen size of 450 x 450 x 125mm was defined.

Since one end-use of this material is to be a capability to rapidly upgrade the potential resistance of a existing structure, a major consideration is that age to gain sufficient strength to resist attack must be minimised. Without using fine-ground cements and/or concrete admixtures, the extent to which the commissioning time may be reduced is limited, however it was felt that an age-to-test of three days represented a reasonable compromise.

All mix designs were developed assuming completely dry aggregages. Since it is not possible to justify this assumption with available material, a moisture content calculation, using a standard siphon-can test (British Standard 812 (7)) is carried out on each aggregate immediately prior to casting. The percentage moisture content by dry aggregate mass is calculated, this contribution being allowed for by an increase in aggregate weight and a decrease in weight of water in the final mix designs.

All mixing is carried out in a horizontal rotating pan mixer; the concrete constituents are charged in a standard order, that is, fine and coarse aggregates mixed together before the cement and water are simultaneously added to the mix. For all the various fibre types it was found that the optimum fibre distribution was established by adding the fibre to the already mixed concrete matrix. This ensures a minimum of 'balling' of the discrete fibre lengths. In the case of both the steel and polypropylene fibres, sufficient separation can be achieved by shaking the fibres slowly into the surface of the rotating matrix, through a large mesh. A more rigorous and time-consuming process is necessary to persuade the very fine (12μm) KEVLAR-29 single filaments to separate to an acceptable degree. The procedure adopted is to initially separate the matted fibre by hand to reduce it to reasonably small conglomerations. It is then pneumatically injected directly onto the surface of the rotating concrete so as to further encourage it to separate. The more open mat can thus be worked into the concrete by the action of the mixer paddles. Whilst this

method does not ensure a complete separation of all the fibre conglomerations it does give a composite mix of reasonably uniform appearance, becoming less acceptable towards the maximum fibre volumes which can be incorporated. In a field situation it would perhaps be more viable to use a technique in which the sprayed concrete passes through a pneumatically held curtain of fibre, though the practical problems of this kind of approach have not yet been fully considered.

All specimens are de-moulded after one day and stored in a standard high humidity room (20 ± 1°C:90% + R.H.) until immediately prior to testing.

TEST TECHNIQUE

After curing specimens are rigidly fixed in a target frame offering firm edge support to the back face of the specimen, with the 450mm square cast face pointing towards the projectile firing equipment.

The projectiles are fired remotely in an enclosed 20m long firing range. A 7.62mm diameter rifle barrel is attached to a pressure housing incorporating a breech, firing pin, bolt and trigger mechanism with safety catch. The pressure housing is itself rigidly attached to a steel frame which in turn is bolted to the range floor. The trigger mechanism is connected by a detachable linkage rod to an 11.4kg pullout, 18mm stroke length mains solenoid. For safety reasons the solenoid is activated remotely using a firing box fitted with an arming key and off-biased switch. Connection wires are coaxial and a capacitor is used across the switch to reduce electrical interference with ancillary equipment.

Bullet velocities are monitored using photodiode-based trigger circuits to start and stop an electronic timer. Usually, two stations are used, placed close to the target and one metre apart, although the option of using three stations, both to give a velocity check and also to calculate deceleration, is avaialble. The timer is triggered by a change in voltage output experienced by the photodoide circuit when the bullet passes between a focussed light source and the light-sensitive photodiode. A 70-80% success rate is normally achieved with this equipment, failure being due usually to external interference causing premature triggering.

High speed photography is being used in an attempt to capture the detail of the impact event. Using a Barr and Stroud rotating mirror camera, capable of a framing rate up to two million frames per second over 30 frames, a series of photographs of the bullet in flight taken at 1.5μs interframe has been produced. The variable nature of both the bullet detonation and the velocity in flight make it difficult to accurately predict the time to impact of the projectile with any degree of precision (relatively to the camera's capabilities). Hence, any attempt at photographing the bullet in this way must carry only a limited probability of success. In order to offset this, a rotating prism camera, capable of up to 20,000 frames per second is also being used, though this is not capable of the same amount of detail.

Various types of detector to measure crack velocity, spall characteristics, stress wave propagation and projectile retardation through the target are also under development.

POST TEST ANALYSIS

Damage to an impacted target consists of front face spall damage, a burrow and possibly back face scab damage. Spalling and scabbing result in craters being formed, the extent of damage may then be quantified in terms of the dimensions of these depressions. With fibre inclusions a lot of damaged material remains loosely attached to the target. This is removed to expose the true crater whose depth at various grid points can be found using a specially constructed rig with depth gauge connected to a displacement transducer which in turn is connected via an analogue/digital converter to a micro-computer. This automatically produces crater profiles and calculates crater volumes. Details have been given by Anderson et al (6).

Preliminary tests in which target perforation occurred showed that the projectile exit hole was rarely in line with the initial impact hole. Deviation of the projectile from its original flight path must have taken place within the target. Since to assess the resistance of the particular specimen it is necessary to measure the penetration path length, a 150mm diameter core is taken perpendicular to the target front face and containing the damaged section of the sample. If the slab has not been perforated, thin slices are sawn from the rear face of the core, and parallel to it, until the hardened steel tip of the projectile is encountered. Using both this point and the entrance position of the projectile, a most probable path may now be estimated to allow the core to be sectioned, thus exposing the burrow formed in the composite.

RESULTS AND COMMENT

This experimental programme is still in progress and very few statistical series have been completed, these serving only to establish the arithmetical correctness of the microcomputer based analysis. Various practical difficulties have yet to be overcome, including control of the aggregate moisture content and a valid method of assessing its contribution to the concrete matrix. Since using the dry mix spraying process water/cement ratio is controlled by the spray gun operator, it is important that a fundamental understanding of the effect of varying water content is attained. It is considered that, providing a rigorous control of the fibre concrete constituents can be ensured, the surface response theory approach should give an acceptable solution, within the limits dictated by the nature of dynamic testing.

Experimental work is proceeding to establish the mechanisms of failure and also to record the characteristics of the overall impact event. Examination of a sectioned sample, after penetration, typically shows a crater of approximately 100-130mm diameter and 30-40mm depth developing into a burrow, which may be straight for the first 20-30mm. However, probably at the point where the copper jacket strips from the hardened steel core, the penetration path deviates from the original flight path (i.e. normal to the impact face) by an angle of up to approximately 80°, the position of this deviation is marked both by the presence of the jacket and also by a local widening of the burrow, as shown in Plate 1.

The hardened steel core may then continue along the new straight path for a distance of up to 70-80mm before coming to rest, Plate 2. Alternatively the same sort of distance may be travelled on a curving path, Plate 3, which may, in extreme cases, lead to the projectile coming to rest in a direction totally opposite to its orientation on entry, Plate 4. It should be noted that these targets have been sectioned and the full thickness is not shown in Plates 3 or 4. If the change of projectile direction is extreme, and perhaps dependent upon whether the core is in collision with aggregate or mortar immediately after the copper jacket is stripped, the hardened steel core may undergo a stress which exceeds the material strength, hence the core fractures and rapidly comes to rest, Plate 5.

Preliminary penetration tests carried out on specimens prepared to determine the maximum volume of KEVLAR-29 which could be incorporated in the concrete mix indicated an interesting trend. In several cases it was observed that normal penetration depth, as opposed to penetration path length, was much lower than expected because of gross deviation of the projectile during penetration. This change in path seems to have occurred as the projectile travelled through conglomerations of fibre within the composite. These conglomerations of fibre were a result of trying to incorporate too much fibre in the mix. This behaviour suggests that the projectile may be induced to deviate during penetration by incorporating a series of "relative voids" (compared to the desnity of the concrete) into the composite. First indications are that the voids need to be slightly smaller than the projectile length to induce instability.

Some problems exist with this type of approach however, the first being that it is necessary to fully understand the mechanisms involved in the projectile/composite interaction in order to ensure that deviation does occur. Another problem is the reduction in structural integrity which will result from deliberately including voids in the concrete. It may perhaps be necessary to restrict the use of such a material, employing it solely for up-grading pruposes on existing structures. The difficulty of ensuring a reasonable distribution of "relative voids" using

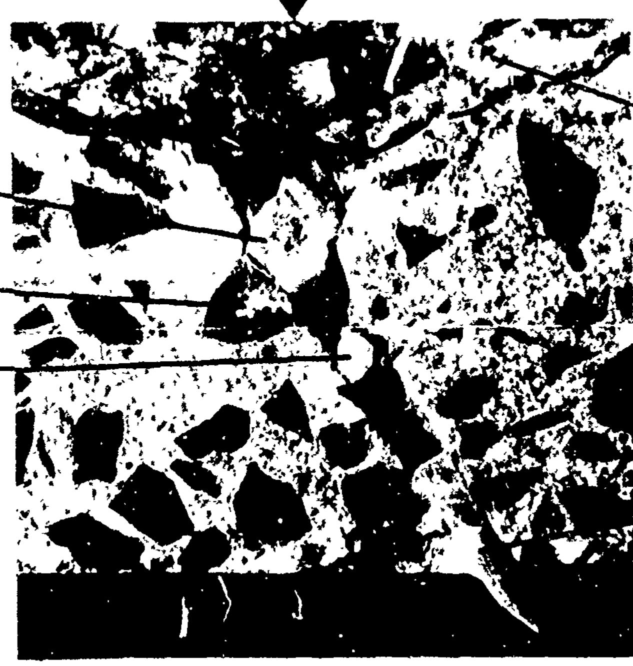

Plate 1 Penetration of hardened steel core projectile through a fibre reinforced concrete target showing deviation of projectile path where sheath is stripped from projectile core

Plate 2 Deviation of projectile along a straight path

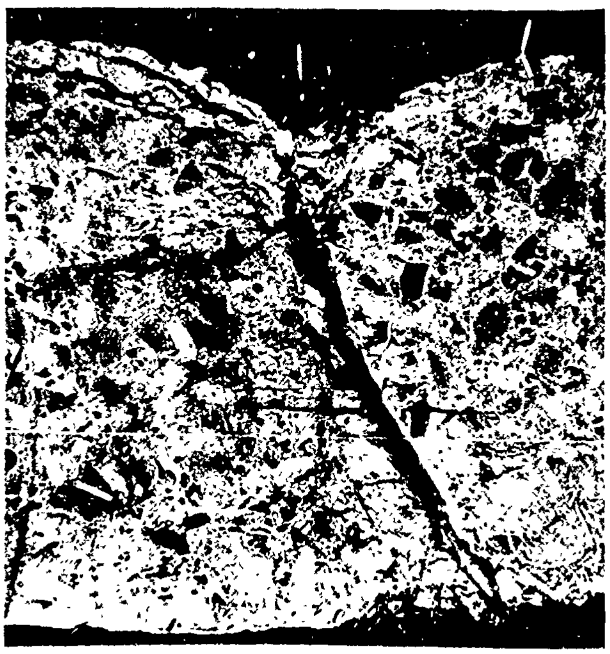

Plate 3 Deviation of projectile along a curved path

Plate 4 Deviation of projectile to complete a U-turn

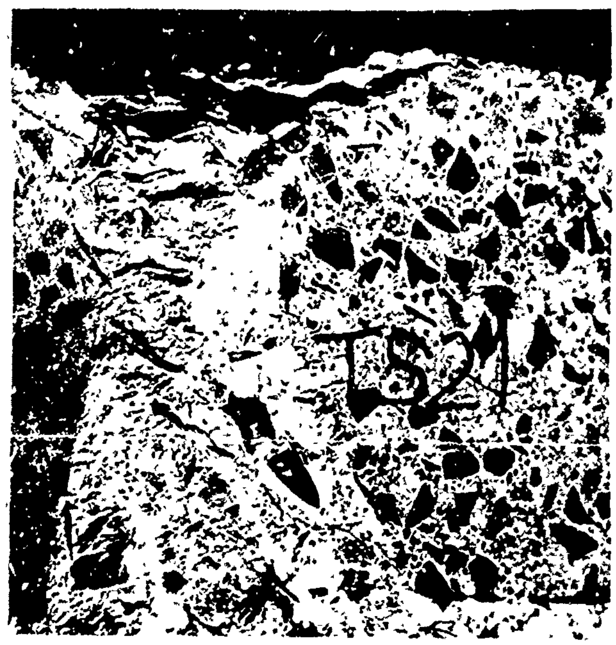

Plate 5 Deviation of projectile causing fracture of the hardened steel core

a sprayed concrete process would also need to be overcome.

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